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A systems approach to evaluating sustainability of biofuel systems

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ABSTRACT

Biofuels are evolving in complex systems of interrelating environmental, economic and social issues. For this reason a number of sustainability criteria covering these issues have been developed. However, there has been little effort given to the development of a mechanism to evaluate compliance of biofuel systems with the sustainability criteria available. Grounded in the theoretical and practical insights from systems thinking and literature on indicator selection processes, this paper intends to extend the existing discussions on the sustainability of biofuels by providing a critical review of biofuels sustainability literature and providing a conceptual framework to guide thinking about measuring, monitoring and evaluating sustainability of biofuel systems. The paper focuses on the integration of social, economic and environmental issues to establish holistically the sustainability of biofuel systems. The paper established that monitoring and evaluation indicators should reflect: (i) all the processes involved in the life cycle of biofuels; (ii) interrelationships of subsystems and related impacts; (iii) different subsystem perspectives (economic, environmental, and social); and (iv) a process of continual learning, which facilitates improved functioning of the entire biofuel system.

Contents

1. Introduction

Biofuels present a complex system encompassing a diversity of issues within the social, economic and environmental sustainability domains. These issues and their interaction have raised a lot of interest in studies that integrate environmental, economic and social issues (e.g. [1,2]). Examples of such discussions are presented by Leontief [3], Daly [4] and more recently Freire et al. [5] who developed and applied the method "Life Cycle Activity Analysis—LCAA", which integrated economic oriented Koopman's Activity Analysis and the environmental oriented Life Cycle Assessment method. Some aimed at optimum solutions for sustainability (e.g. [5]), disregarding the nonlinearity and time dependence of the interactions of environmental, economic and social issues and therefore ignoring time and distant cumulative impacts. It has also been argued that, given evaluations of

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sustainability issues are complex, any evaluation of such issues should seek to provide a mechanism for learning for better understanding and management rather than seeking optimum solutions [6].

In the biofuels area some factors that will influence the future of biofuels have already been identified, and these include demographic features (e.g. population and consequent impact on fuel demand), technological changes, growth in biofuel markets, and other community dimensions influencing the biofuel related decisions [7]. In this paper it is accepted that any evaluation of biofuels systems should provide mechanisms for learning to better manage and organise biofuel systems.

To date, a wide range of publications providing insights into the social, economic and environmental issues related to the development of biofuel systems have been produced by academics, state governments, government agencies, non-governmental organisations, and international agencies seeking to identify the key sustainability issues in biofuel developments. Notable contributions include the UN- Energy's (the interagency formation on energy under United Nations), Sustainable Bioenergy: A Framework for Decision Makers' [8], United Nations department of Economic and Social Affairs' (UNDESA) Sustainability Criteria for Small Scale Production and Use of Liquid Biofuels in Sub-Saharan Africa: Perspective for sustainable Development [9], the World Wide Fund for Nature funded, Sustainability Standards for Bioenergy [1], the German Federal Ministry for Economic Cooperation and Development Commissioned study on the criteria for assessing biofuels in developing countries [10] and the EU's “Proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources” [11]. These publications share the following common conclusions:

- Biofuel systems are complex systems characterised by interacting human and natural systems. They are characterised by trade-offs between social, economic and environmental dimensions of biofuels sustainability.
- There is need for a holistic approach which integrates social, economic and environmental issues to determine the sustainability of the total biofuel system.
- Spatial scale issues influence sustainability outcomes with community oriented decentralised systems scoring high on improving local sustainable development and centralised production systems scoring high on economies from scale production.

Notably, there is significant amount of comprehensive studies on economic and environmental sustainability issues but social issues are still under studied in the biofuel literature. Social issues in development projects are, however, receiving increasing international support with international agencies such as the Inter-American Development Bank, UNESCO, World Bank and OECD investing considerable effort in the development of social capital [12]. Despite this international effort, there is very limited effort towards understanding social sustainability issues of biofuels. The literature on social sustainability of biofuels has tended to focus on providing a means to fight poverty in the less developed parts of the world through the creation of biofuel enterprises and the consequent employment creation and income generation, local ownership, local access to energy, workers' rights, community relationships (e.g. land use and tenure conflicts), participation and impacts on food production (e.g. [7,8,13]). As such, decentralised production systems have been recommended in such regions which have potential advantages of being socially inclusive enabling disadvantaged members of a community to participate in sustainable development issues and empowerment through local ownership and access to resources [4]. These issues have been discussed in several publications with little effort towards developing indicators for measuring success. Indicators and measures are therefore required to measure progress towards achieving these social dimensions in integrated systemic assessments that also account for interrelationships with economic and environmental sustainability.

There has also been little effort in establishing mechanisms for evaluating and monitoring compliance with the proposed sustainability criteria to reflect system performance and sustainability. To measure compliance with sustainability for complex biofuel systems requires an integrated approach encompassing social economic and environmental dimensions to reflect the whole system's characteristics. Conducting an integrated evaluation that reflects such issues presents a daunting task due to huge information demands; the need to coordinate interacting social, geopolitical, economic and natural systems; and the interdisciplinary requirements of skills, it is however needed to provide an understand of different perspectives and evaluate system components jointly [14]. The theoretical and conceptual ideas underlying systems thinking and complexity theory provide the basis for such an evaluation.

Grounded in the theoretical and practical insights from systems thinking and literature on indicator selection processes, this paper intends to extend the existing discussions on the sustainability of biofuels by providing: (i) a conceptual framework to guide thinking about potential indicators that can be used to measure, monitor and evaluate sustainability of biofuel systems; and (ii) identify specific indicators that illustrate systems thinking. The latter focuses special attention on the applicability of social indicators in biofuel systems and how these can be integrated with environmental and economic issues to establish the sustainability of the whole system.

2. Systems approach in monitoring and evaluation

Monitoring and evaluation is central to management and understanding of systems because it plays a critical role in:

- providing a basis for accountability and management [15–19];
- knowledge building, fostering learning and development [6];
- identifying problems and impacts of problems [18,19]; and
- enabling public awareness of impacts [18].

Central to monitoring and evaluation is the need for tools to facilitate such an evaluation.

Indicators are the frequently used tools to (i) signal the need for response to threats or opportunities, whilst providing a mechanism for measuring and communicating information vital for decision-making; (ii) assess compliance of development projects with sustainable development aspects; and (iii) directly influence behaviour [20,21]. Indicators convey a complex message in a simplified informative form [21,22]. The importance of indicators in monitoring and evaluation of systems has international recognition. For example, Agenda 21 stressed the need to establish indicators of sustainable development to aid decision-making [23]. There has been growing acknowledgement of the need to build on the principles of systems theory in monitoring and evaluation of complex systems. A systems approach to evaluation has a potential to identify a wider variety of outcomes incorporate on going learning and allows for adaptation of emergent properties [9]. These issues are more important for an emerging biofuel sector with a host of environmental, economic and social factors interacting in a nonlinear fashion.

Issues concerning systems theory have been detailed in a number of publications (e.g. [24]—see also preface by Ervin Laszlo in this reference; [25,26]). It is generally accepted that systems

theory is based on the principle that the understanding of system content and context requires an appreciation of the properties of the whole system, including interrelationships of parts and the feedback processes and how all this influence the whole system [27]. Critical to systems theory is that, “any reduction of the whole to parts limits the understanding of the system” [27]. Systems theory entails a trandisciplinary, interdisciplinary and multidisciplinary approach to evaluation of systems [25].

Other authors have characterised systems approach into soft and hard systems e.g. [28,29]. This study is not particularly interested in these debates but explores the possibilities of the application of a holistic approach to provide an understanding of the often-disintegrated social, economic and environmental evaluations of biofuel systems. The challenge is therefore to develop evaluation tools that reflect the principles of soft systems, which emphasises the need to account for multiple causality, plurality of perspectives, interrelationships and trade-offs in subsystems to better understanding the whole system [28].

The available biofuels sustainability criteria, as documented by organisations such as the United Nations and European Commission, provide an important evaluation step by highlighting sustainability standards biofuel systems need to achieve. A second step is then to develop a set of indicators to monitor and evaluate the sustainability of biofuels to enhance systems' learning guided by the existing sustainability criteria. To ensure easy validation of information provided by indicators, scientific credibility and value of indicators, there is a need for indicator selection procedures that account for these issues [21,30,31]. In the case of biofuels, characterised by diverse sustainability issues, such procedures are vital where indicators have to capture the complexity of biofuel systems whilst remaining simple and informative. A systems based derivation of indicators becomes necessary to capture such complexity.

A systems based derivation of indicators is not a new idea. Bossel [15]) provided systems based practical procedure to determine suitable indicators to monitor and evaluate agricultural systems. The US National Commission on Science for Sustainable Forestry recommended the need for a systemic, transparent and logically structured indicator selection procedure [31]. More recently, Niemeijer and de Groot [32] provided an indicator selection conceptual framework grounded in causal relationships influenced by the widely quoted driving force-pressure-state-impact-response (DPSIR) framework (see [33]). DPSIR depicts causal chains with social and economic influences exerting pressure on the environment and therefore causing not only environmental impacts and the consequent changes of the environmental state, but also socio-economic impacts which trigger response through corrective measures on the driving forces (e.g. economic and social factors) [34].

Such a conceptual indicator selection framework can “potentially play an important role in the indicator selection process and in developing consistent indicator sets that are not primarily selected on the basis of individually applied criteria, but on how they are interrelated through causality” [32], p. 15.

Structured indicator selection frameworks have been criticised for being reductionist “tending ,toward the expert-led development of universally applicable indicators that do not necessarily emphasise the complex variety of resource-user perspectives” [19], p. 2. The complex diversity of system views requires different stakeholders and communities to work together ensuring participatory approaches in indicator setting [35]. However, validity and scientific credibility of indicators obtained from these processes is not always ascertained [35]. Participatory approaches to indicator setting and monitoring are also considered demanding on both the time and effort of communities who may require clear incentives to participate in such processes [19,36]. To this extent, Reed et al. [19] argued for an indicator selection process that combines Bossel's [15] procedure, perceived as reductionist, with participatory perspectives in indicators' selection, and monitoring and evaluation to accommodate the plurality of issues characterising a system while ensuring scientific credibility. Expert inputs into participatory processes may therefore provide a minimum set of indicators that can guide the processes for further indicator development through bottom-up approaches.

3. Obtaining a conceptual understanding of biofuel systems

The previously discussed literature indicates the critical need to develop mechanisms that capture essential parts of a system holistically while accounting iteratively the plurality of issues constituent in system parts. Drawing insights from this literature, this section first, provides a conceptual framework to guide a holistic understanding of biofuel sustainability issues. Second, the section discusses an illustrative literature drawn set of indicators that support monitoring and evaluation, and demonstrates how biofuels' system learning could be facilitated.

Conceptual frameworks enable logical structuring of problems, parts identification and translation of abstract theory into specific variables and aspects that can be practically examined [37]. The process of establishing the framework involves identifying key dimensions, each considered critical in the process of understanding the sustainability issues of biofuels and hence system learning (Fig. 1). Dimensions identified as key to this understanding include (Fig. 1):

- Processes
- Perspectives
- Interrelationships
- Adaptability

3.1. Processes

The “processes dimension” recognises that biofuel systems involve a collection of interrelated tasks and activities (e.g. energy crops production, biofuel processing, marketing and end use applications) that influence social, economic and environmental outcomes. Processes involved in biofuel systems have traditionally been presented to reflect fuel chains including feedstock production (e.g. cultivation, harvesting, agricultural waste utilisation) conversion processes biofuel life cycle assessments e.g. [38,39]. In some life cycle assessment studies, the production chains are moved back to also analyse the production of agricultural inputs used in producing biofuels including mechanical and equipment production to account for the involved energy input, emissions and economic costs e.g. [39,40]. However, these analyses exclude other important social processes that influence the overall sustainability of biofuel systems.

Planning processes and the resulting operational biofuel models applied, often excluded in most evaluated biofuel processes, are likely to influence biofuel sustainability outcomes. The biofuel enterprise model detailing the organisation and management (e.g. private or community enterprise), scale of operation and social processes involved in instituting such organisations are important for the overall performance of the system. Accounting for these social processes in addition to the dominantly accounted for physical biofuel production processes and end use applications has important implications for holistic system understanding.

Planning for biofuels' sustainability is a crucial strategic stage that not only ensures environmental and economic accountability of biofuel systems but important social sustainability dimensions

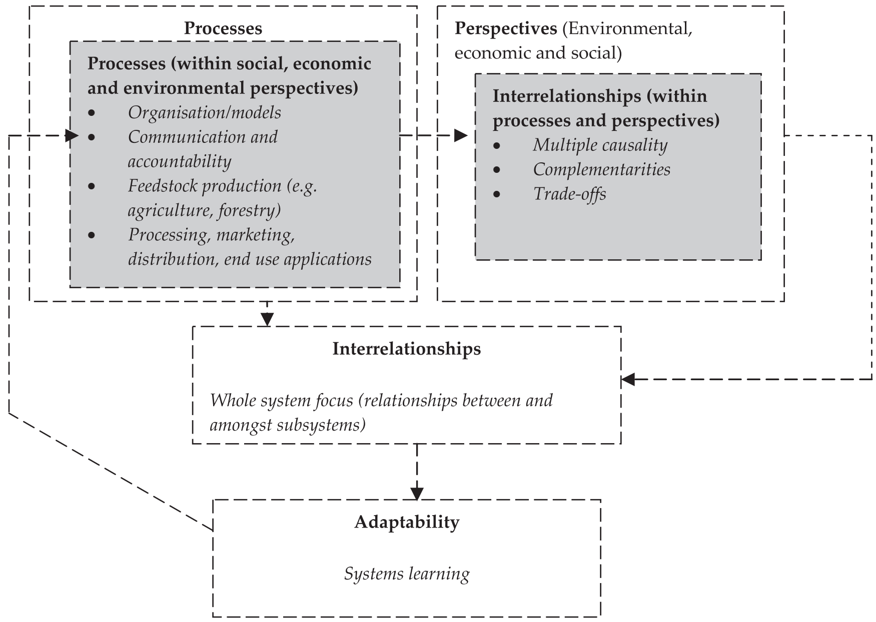

Fig. 1. Conceptual relationship of the key system dimension.

such as social inclusion, participation, ownership, empowerment and institutional support systems. A key emerging issue in literature on adaptive management is the need for stakeholder (including communities) involvement, not only in monitoring and evaluation of systems, but also in planning processes, feasibility assessments, and the communication of outcomes and impacts to enhance adaptive management through collaborative learning and action [41–43]. The establishment of stakeholder-based learning networks could provide mechanisms to facilitate the understanding of biofuel systems. Such networks enhance collaborative action and learning [42,43].

3.2. Perspectives

Processes identified above constitute different biofuels subsystems (e.g. planning and cropping system). The “perspective dimension” recognises the need for in-depth understanding of these subsystems to accommodate different perspectives in establishing the sustainability of the whole biofuel systems. This is in recognition of that biofuel systems integrate different processes (as discussed above) that yield different social, economic and environmental sustainability outcomes. This is also in recognition of the need for different methodological approaches suitable for different subsystems. Jansen and Vellema [44] argued that no single methodology can bring together all sustainability entities of biophysical and social sciences, and hence the need for mixed method approaches to enable holistic understanding of systems. For example, Jansen [29] argued that constructivist approaches were important to the extent that they detail social aspects of farming systems but missed other crucial natural science oriented aspects of farming systems.

Jansen and Vellema [44] argued for integration that recognises perspectives emergent from detailed subsystem studies before seeking interrelationships and trade-offs emergent from such studies in integrated evaluations. There is therefore a need to incorporate insights from different perspectives before integration to have an in-depth understanding of subsystems. Identifying different perspectives ensures that no important aspects of a system are missed [39]. Bossel [15] also argued for identifying system components before establishing their contribution to the total system because each component has “characteristic functions that orient interest”.

The “perspective” dimension is also influenced by Cabrera et al. [25] who argued that any concept or understanding must have a reference frame that establishes focal points from which attribution occurs to establish subject-object relationships. Focal points in understanding the potential roles of biofuel systems are evident in biofuel sustainability discussions. For example, decentralised systems have been advocated on socio-economic grounds and sustainability discussions are socially orientated, which have limited detailed studies on the understanding of the environmental performance of such systems e.g. [45,46,47].

On the other hand, the focal point of biofuels sustainability in the developed world has been more environmental performance orientated as evidenced by the dominance of emissions studies in life cycle assessments in such countries e.g. [39].

In-depth understanding of subsystems need not be an end but a step in the process of holistic understanding pursued in integrated studies. However, subsystem understanding has been the characteristic nature of biofuel studies, with advocacy mainly driven by emission reduction potential of biofuels while opposition was mainly driven by social concerns particularly, food security concerns e.g. [39,49]. It is therefore vital to obtain a holistic contextual understanding of biofuel systems. The starting point of analysis, as noted above, depends on the primary drivers of the biofuel system or interest orientation of the researcher (e.g. social objectives in decentralised systems). What is vital, regardless of the starting point, is the establishment of interrelationships emergent from different perspectives and the extent to which they combine interactively to influence the sustainability of the whole system.

3.3. Interrelationships

Different processes, as noted above, yield different outcomes with implications to varied sustainability perspectives. This study, however, recognises that different processes combine interactively to influence the whole system. For example, the cultivation of crops has implications on environmental sustainability through a number of issues including the potential for carbon sequestration

of the crop involved, water and soil nutrient demand and related implications and other desirable agronomic characteristics of a crop, for example, low fertiliser demand [29,39]. These issues have implications on human dimensions such as economic, cultural and social issues regarding farmer perceptions of the crop and farmer's willingness to adopt the crop as influenced by factors such as the returns of the crop compared to other potential crops [29]. Even when the crop is grown, other issues such as the availability of biofuel markets, as detected by consumers, will determine continuity. Therefore, the natural and social systems are mutually supportive and the tenants of such relationships require integrated studies.

The “interrelationships dimension” considers the interaction of different system components in influencing sustainability outcomes. Establishing relationships of different aspects enhances connectivity, an understanding of the contribution of component parts to the whole system, and therefore, an understanding of the functionality of the whole system [15,25]. Thus, there is need to use data from social research approaches (e.g. interpretivism/constructivism) to understand the more social oriented perspective in combination with more positivist approaches applied to provide understanding of natural system variables often not obtainable through social research processes (e.g. the extent of soil carbon sequestration, emissions reduction potential) and hence providing a mechanism for integrated eveluation. Lin [48] argued for the application of positivists and intepretivist approaches in a single study to identify causal relationships (positivism) and causal mechanisms (interprevism) in data. Such an approach is also recommended in Patton [49] who stated:

> Rather than believing that one must choose to align with one paradigm or the other, I advocate a paradigm of choices. A paradigm of choices rejects methodological orthodoxy in favour of methodological appropriateness as the primary criterion for judging methodological quality. The issue then becomes not whether one has uniformly adhered to prescribed canons of either logical positivism or phenomenology but whether one has made sensible methods decisions given the purpose of the inquiry, the questions being investigated, and the resources available. The paradigm of choices recognises that different methods are appropriate for different situations (p. [38,39]).

Patton's criterion of ‚methodological appropriateness' supports the need for using both positivist and interpretive obtained data to answer research questions in the enquiry of different aspects of biofuel sustainability to enhance the quality of the study. This also supports the ‚perspectives' dimension of the conceptual framework, which acknowledges the need for in-depth understanding of subsystems using appropriate methods before integration.

In this case, holism implies the understanding of whole system built on data generated from various relevant and necessary approaches, which are integrated through the identification of interrelationships of different sustainability issues rooted within the social, economic and environmental perspectives. Holism is vital to this conceptual understanding, however, with some level of flexibility in the processes of data generation and establishing indicative interrelationships and trade-offs that informs system sustainability.

3.4. Adaptability

The “adaptability” dimension considers the meaning and role of system's outcomes through the identified functioning of subsystems and their interconnectedness to monitor, evaluate and manage biofuel systems. This dimension, therefore, highlights the need for reflection on the observed outcomes to allow for multiple responses to various imperatives fostering learning. The sustainability implications are drawn from information that relates to an impact or outcome, guided by the processes involved in the system, the interrelationships and multiperspectival issues surrounding the system. This allows learning from the processes involved and therefore gives the capacity to make strategic and operational changes to match the changing environment, new knowledge and experiences.

The establishment of stakeholder-based learning networks, as highlighted in the “processes” dimension could facilitate collaborative learning and action to enhance the understanding of biofuel systems. The learning networks will involve pooling different disciplinary expertise in problem formulation, research design, data analysis, integration of different disciplinary contributions, the communication of findings and further action strategies to improve the systems [50,51]. Learning networks, therefore, provide mechanisms to implement the integration of social, economic and environmental aspects of biofuel system in a coordinated manner enabled by shared problem definition amongst interdependent stakeholders. It is inevitable that in such a process there will be a need to integrate both subjective and objective aspects for the understanding of the whole biofuel system.

4. Biofuels sustainability indicators

To apply the conceptual framework discussed above, there is need for developing contextual-based set of indicators that aid the understanding of biofuel systems through adaptive management. A number of sustainability indicators can be identified from studies evaluating biofuels from different perspectives. However, there has not been limited attempt to analyse information portrayed by such indicators in an integrated manner to reflect the contribution of biofuel subsystems to the whole system sustainability. Whilst most indicators are largely influenced by study objectives, some carry information that can be used or extended to reflect subsystem interrelationships and therefore the combined and interactive influence on system sustainability. It is against this background that this section will proceed by reviewing indicators traditionally used in biofuel studies and reflect on how they can be used in an integrated assessment. In cases where indicators are not well developed, such as in social sustainability studies, lessons are drawn from indicator applications in other fields.

4.1. Environmental indicators

A number of studies have evaluated greenhouse gas emissions from lifecycle production of biofuels and compared the results to lifecycle emissions of conventional fossil fuels to reflect the possibilities of emissions reductions/savings from biofuel use e.g. [39,52]. In this case, emissions savings from biofuels' use relative to fossil fuels indicate the comparative environmental performance of biofuels e.g. [53–55].

Emissions reduced from an inefficient use of land, however, do not constitute a sustainable biofuel system [38,39,56]. Biofuels' land demand will compete with other land use, including food production, forestry and physical infrastructure developments e.g. [46,57].

Improved land use productivity and hence efficient land use lowers the need to divert more food land to energy crops, conversion of forestland to crop land and the consequent biodiversity and soil carbon losses [54]. Crop yields and energy yields per hectare are important determinant factors for land use efficiency of biofuels [55,58]. Therefore, emissions per given land

area and period of production (e.g. CO_2/ha/year) has been used to account for land use efficiency in relation to greenhouse gas emission reduction [39].

Alternatively, emissions per energy yield from a hectare of production per given time period have also been used to link land use to energy output and the resultant emissions burden or savings. This indicator also gives valuable indications on the cropping systems that improve output per land use whilst measuring the emissions burden or savings for such a result.

The emissions per energy output coming from energy crops produced from a hectare could also be linked to economic viability of biofuels. In this case, a hectare of crop production can be used to reflect both the environmental burden/benefits (e.g. emissions savings per ha) and economic benefits/costs emanating from putting a hectare to the production of energy crops (e.g. profits/ha/energy output on that hectare). Other environmental impacts can be linked directly to human lives in a similar manner. For example, the amount of land for food production displaced by energy crops production or the output of food per given land area used to produce energy crops may show the social impacts of crop energy biofuel systems.

Human intoxication often results from emissions such as carbon monoxide, sulphur and elevated nitrate and nitrite in drinking water [59]. The transportation of agricultural chemicals and fertilisers, through leaching and surface run off, cause eutrophication (growth of algae in water bodies due to nitrate and sulphate fertiliser leaching) which affects aquatic life when algae decay and deplete oxygen supply [60]. Measurements of these pollutants have been obtained traditionally per unit of land area providing a link with economic and other environmental issues [61,62]. Such linkages, which are lacking in biofuel assessments, could reveal important system interrelationships in integrated assessments.

Whilst emissions per energy output or an area of crop production provide important lessons regarding land use, and therefore the need to improve cropping systems, this however, could overshadow other system improvements that can increase the emissions reduction potential of biofuels. For example, end use technologies and end use applications (e.g. transport or electricity generation) contribute to the ultimate emission reduction potential of biofuels [63]. Emissions reduction potential of biofuels with application in transportation, for example, has been measured by emissions per vehicle-kilometre, which account for the contribution of the end use technologies and application to total emissions [64]. This is an indicator, important for linking processes within the environmental subsystem. However, linkages with other subsystem can be achieved by using quantity of fuel or energy content require to complete a kilometre for a given vehicle linked back to the land used to produce it. Since economic benefits/costs can also be linked to unit area of land such as hectare (e.g. $/hectare), this common link can provide the connection.

Land use changes have raised concerns about biofuels potential to emit soil carbon due to intensive cropping, which reduces soil organic matter content, increases soil erosion and leaching ([65]. Soil organic carbon, derived mainly from plant matter, could have benefits such as aiding long-term plant productivity, decreased erosion, better soil tilth and improved water retention [66,67]. Various studies have shown that the general impact of converting land from natural cover to intensive annual energy crop production decreases the organic matter content of the soil, increases erosion and metabolic losses caused by increased soil temperature and aeration [67]. The resultant soil carbon loss in biofuel production systems could negate the greenhouse benefits. The level of soil carbon has been assessed in mass (e.g. tonnes) per land area, normally a hectare e.g. [68,69]. However, soil carbon is extremely difficult to measure and existing methods are extremely expensive especially in short-term applications (e.g. less than 5–10 years) [68].

Land use change, especially from natural forests to annual crops, affects the composition of flora and fauna [70]. Such changes disrupt food chains and displace food sources causing a decline in many species [71]. For example, in Indonesia 18 million hectares of land have been cleared to make way for palm oil cultivation, which is threatening the existence of orang-utan and Sumatran tigers [72]. This loss of biodiversity can negate carbon savings relative to fossil fuels since these forests sequester carbon. For example, the Stern Review reports that deforestation is responsible for 18% of anthropogenic greenhouse gas emissions [73]. For this reason, the EU Renewable Energy Directive proposed a biodiversity criterion that restricts biofuels made from land with high carbon stock, wetlands, peat land and forested land [74].

Changes in populations of flora and fauna, migration patterns and the loss of carbon sequestration capacity could provide important indicators under this impact category.

4.2. Economic indicators

Economic indicators have been used at various biofuel adoption levels including international, national, industry, farmer and consumer. Key variables measured include investment costs, costs of production, prices of biofuels, other agricultural commodities, investment returns, profitability and employment e.g. [75,76].

The economic concerns from an international view include the impacts of international policies, global prices of biofuels, how global biofuel production affects global food prices in food vulnerable regions of the world, whether nations are meeting national biofuel production mandates, and international certification of biofuels [2,77]. Subsidies are used in certain regions of the world to boost biofuels production. For example, the European Union provided €90 million in subsidies through the Energy Crop Scheme to promote cultivation of biofuel feedstock on 2 million hectares of land [72]. These issues are being monitored by keeping track of biofuel global production quantities, energy crop productivity, global demand and global prices of biofuels e.g. [78]. Worldwide venture capital and private equity investment have also been used to monitor worldwide investment in biofuels to establish future capacity of biofuels [79].

Indicators such as contribution of biofuels to gross domestic product, national quantities of biofuel production, share of biofuels production in agriculture sector, produced changes in fossil energy prices, changes in prices of food relative to biofuel production, and employment levels are used at national level to monitor the contribution of biofuels to the economy e.g. [74]. Since biofuels are one means to abating greenhouse gases emissions, it has been of interest to compare the investment costs of such abatement to other strategies to ascertain sustainability. For example, Kutas et al. [80] estimated that the cost of reducing one tonne of CO_2 through ethanol application is between €600 and €800 as compared to €24 through EU's emission trading scheme implying ethanol production was a costly means of such mitigation. However, this requires linkages with other biofuel advantages (e.g. employment creation, fuel supply security) beyond emissions abatement costs, which may credit the system and therefore lowering the total costs.

Farmers, processors and distributors' (the Industry) adoption of biofuels are driven largely by commercial viability of respective biofuel enterprises [81]. Indicators such as return on investment and internal rates of return have been used to appraise such investments. For operational biofuel programmes, a number of studies have placed importance on operation and capital costs, energy crop prices, biofuel and fossil fuels prices (to monitor

competitiveness), return on investment and crop productivity per given land area, normally a hectare, have been used as indicators to monitor and evaluate commercial viability [82].

The challenge in an integrated study with the objective of obtaining a systems understanding is to be able to relate information from these economic indicators to the environmental and social issues of biofuel sustainability. Whilst such a system level analysis has not been done, there are units of measurement in use that could be extended to show how the economic subsystem can be related to social and environmental subsystems. Section 4.1 has already provided an example of how financial benefits could be linked directly to environmental impacts by measuring viability and environmental burden per area of production (e.g. CO_2/hectare and cost of output/hectare). The economic evaluation literature also links economic variable such as lifecycle costs to energy output (e.g. $/MW h) to measure the cost of producing a unit of energy e.g. [52,56]. Measuring environmental burdens/benefits per unit of energy output is also common in most LCA studies. Therefore, energy output can connect economic benefits/cost and environmental benefits/cost just like a hectare of production to give a picture of both economic and environmental sustainability of biofuels.

4.3. Social indicators

Social indicators have traditionally focused on the people affected by a project, what happens to them when affected, and the likely social changes and impacts on social stability as a consequence [83,84]. The impacts of biofuel production on food supply and cost are the commonly discussed social indicators [85,86]. Implications of biofuel related emissions or the reduction in certain types of emissions (e.g. carbon monoxide) on human health is also a key social issue e.g. [1,64,87]. However, other indicators of human well-being and quality of life such as social capital development, trust, cultural values in relation to the implementation of biofuels are still limited in biofuels literature. Such social indicators, however, are commonly applied in other fields including education, health, governance, economic development, family psychology and natural resources management e.g. [12,83,88,89]. Most of the available social indicators are not integrated into biophysical and economic processes to holistically understand sustainability of systems. The challenge is, therefore, to develop social indicators that could be integrated into environmental and economic processes.

The number of businesses started or enhanced due to biofuel enterprises is an important social indicator of biofuels that could be integrated with economic and environmental issues by tying case specific business activities to certain environmental burdens e.g. pollution, emissions. Income obtainable from these businesses per household/individuals could be used as an indicator for welfare. To link welfare improvement to environmental and economic burdens/benefits, income could be measured relative to energy output in biofuel systems. Other indicators such as number of people employed by gender or other relevant grouping and posts held (to measure the quality of employment) and

Table 1
Example social indicators.

Sustainability criteria	Indicator	Methods of measurement
Existing land tenure systems/land use rights should be observed in plans to grow or harvest biofuel feedstocks	• Upholding land use rights • Compensation in cases where land use rights are violated in agreement with communities	• Review of land use rights documentation and implementation levels and enforcement monitoring • Primary surveys/key informant interviews involving land owners
Biofuels should not displace land used for producing vital food crops	• Total hectares of land displaced for energy crop production • Competing uses of crops	• Primary surveys/interviews targeting affected groups • Secondary review of food production (time series data)
Safety and fair wages should be ensured for workers along the biofuel production chain	• Availability of safety procedures • Wages relative to regulated wages	• Safety procedures document review • Enforcement procedures review • Questionnaire surveys directed to employees
Biofuels should uphold or improve intra and external community cooperation	• Number of people involved in a biofuel organisation • Shareholding structure of an organisation • Working relationships and perception of issues • Network partners from the same community/geographical area • Relationships of network organisations • Number of work colleagues in local networks • Frequency of meetings	• Questionnaire surveys • Key informant interviews • Business records review • Observing intra organisational meetings taking note of issues discusses and members/employees contributions • Evaluating contents and nature of member working contracts
Linkages of community with outside world – Funding – Skills Development etc	• Number of partners external to a community • Nature and strength of inter-organisational relationships • Quality and democratic aspects of inter-organisational relationships • Frequency of meetings • Available and nature of inter-organisational support • Inter-organisational expected support of each other	• Longitudinal studies • Observing inter-organisational meetings taking note of content/issues discussed and contributions of each partner organisation • Evaluating inter-organisational working contracts • Identifying informal arrangements and impact on relationship through key informant interviews

shareholding structures (to show level of local ownership) expressed per unit of energy produced provide a means for identifying interrelationships between issues. Since the environmental and economic benefits and burdens are obtainable per unit of energy output, these indicators can easily be analysed to reflect the whole system picture.

Water use during production of biofuel is a social concern as it affects access by human beings and wildlife [90]. Biofuels use water during the cultivation and processing/conversion stages in the production life cycle and during production of the fertilisers used during the cultivation stages [91,92]. Therefore, there is need for an assessment of how water, diverted from shared sources for example, would affect other users. Water consumption per unit energy has been used to measure water use during production of biofuels e.g. [92] but does not reflect on water quality (chemical, physical and biological characteristics based on a set standard) impacts from waste from fuel production processes and fertiliser and chemical run-off. Alkalinity, watercolour, pH, odour, level of dissolved metals or salts, levels of suspended solids and a number of biological metrics are often used as indicators of water quality [see [93] for further details]. Attributing these measurements to biofuel, production can be extremely difficult and may require long-term monitoring of water bodies near agricultural fields. Other related indicators in this regard include populations that might lack access to water due to the diversion of water to biofuel production.

Access to energy by the local people has been discussed as a key sustainability issue particularly in developing countries e.g. [1,8,10]. For this reason, it has been recommended that biofuel use should be encouraged locally. Populations accessing bio-energy in this case will therefore measure progress towards local use of energy at related environmental and economic costs tied to a particular energy output being used by either individuals or a social group.

Networks, shared norms, values and understandings that reflect community cooperation and solidarity are important social capital dimensions [94]. Networks are important for bringing access to resources in a community [95]. The challenge for biofuel systems is to uphold or improve the social capital values that enhance community cooperation and solidarity. Violation of existing land tenure or land use rights (both legal and customary) to make way for biofuels, violation of labour rights through unfair wages and poor safety measures for agricultural workers (competing uses of land or agricultural crops) and ownership conflicts may limit social capital building [1,8–10]. All these issues have the potential to cause social unrest by violating shared perceived rights of local communities (Table 1).

Biofuel systems involve a number of processes undertaken by different agencies therefore creating a network of business relationships, which is a positive attribute to the creation of social capital. These kinds of networks, often referred to as either bonding (internal networking) or bridging (external networking) social capital [95], are vital for unlocking internal and external resources to improve the social wellbeing of a community. Social bonding enhances cooperation vital for the survival of any project in a community.

The discussions above do not provide a complete list of all social indicators that can reflect the social sustainability of biofuels. Some indicators such as trust, mutuality and reciprocity, for example, require long-term associations with communities to understand these values, which may be constrained by the availability of resources [95]. It should also be noted that organisational bonding or bridging at an organisational level might result in social exclusion of non-participating members of a community, which could negatively influence the long term social sustainability of biofuel systems. However, this problem may be alleviated by finding other ways to engage the community in the enterprise, for example, through improving local access to energy by making the enterprise products locally available or other social activities. For these reasons, social indicators may be extended to assess ties with non-participating community members within biofuel systems.

5. Embracing the conceptual framework

Vital to the functioning of the conceptual framework is finding key indicators that reflect all the processes involved and the interrelationships drawing from the functioning of subsystems. One approach identified in Section 2.4 is to establish composite indicators expressing more than one aspect of the system, for example, when income/per energy output or land area used to cultivate to reflect social welfare and environmental burdens of achieving a certain income level. However, not every subsystem aspect can be related to other subsystems by a composite indicator. Most complex social issues may not be easily integrated with other environmental or economic issues using a single indicator. In this case, a multi-perspective indicator approach reflecting different subsystem issues could be applied. The results from each subsystem could be analysed through identifying subsystems' interaction including complementary issues and trade-offs. Therefore, use of composite indicators may need to be complemented with more subsystem informative indicators to accommodate different contributions of a subsystem to the whole system.

While there are inherent challenges of interpretation and use of social indicators in integrated studies with economic and biophysical stressors and changes, this integration is still vital to the understanding of the whole system. This study argues for the use of proxy or surrogate indicators to ensure the integration of more complex social aspects (e.g. trust, culture) into environmental and economic issues. For example, social or cultural acceptability or trust of biofuel system can be indicated (approximately) by the level of community adoptions of biofuels during implementation of such systems. However, other contextual characteristics such as cost of the fuel may induce adoptions in the above example, which may not necessarily reflect acceptance. Therefore there is need to rely on multiple sources of evidence for in-depth understanding. In this case, such proxy indicators applicability may depend on context. For this reason, a case study research, which involves in-depth interpretations of people, topics and issues to establish relationships and outcomes in complex issues allow synthesis and integration of the social data with economic and environmental issues accounting for interrelationships and trade-offs.

6. Concluding remarks

A diversity of issues exists within the social, economic and environmental perspectives of biofuel system's sustainability. A systems approach, therefore, provides a novel method of integrating the evaluation of biofuels' sustainability. The process perspective-interrelationships-adaptability framework enhances a systems approach to the understanding of biofuels through the integration of environmental, economic and social constituent issues along the biofuel production chain. It brings out the multiperspectival nature of biofuel sustainability and establishes connectivity through the evaluation of interrelationships while allowing a process of continual learning through adaptive management. Adaptive management is facilitated by carefully establishing a set of contextual indicators to monitor and evaluate the system.

It should, however, be emphasised that indicators discussed in this paper are top down (as opposed to bottom up approaches) and are not intended to be universally applicable indicators. The importance of bottom up approaches (e.g. participation of stakeholders in the identification and application of biofuel sustainability indicators) in developing indicators need not be underestimated. For effective application of indicators, users need to be involved in their development. The context in which biofuels are diffusing is also important to determining an appropriate set of indicators, particularly for complex social issues. The challenge is therefore, to identify that set of manageable indicators that account for the whole system's attributes.

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